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Thermal desalination using diesel engine exhaust waste heat — An experimental analysis

K.S. Maheswari, K. Kalidasa Murugavel *, G. Esakkimuthu

Centre for Energy Studies, Department of Mechanical Engineering, National Engineering College, K. R. Nagar — 628503, Kovilpatti, Tamil Nadu, India

HIGHLIGHTS

- IC engine waste heat is used for desalinating salt water.
- Shell and tube condenser was used to evaporate the water.
- Water cooled condenser was used to condense back vapor.
- 3.0 l/h distilled water was produced using 5 hp engine exhaust gas heat.

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ABSTRACT

The aim of this work is to utilize the heat energy wasted in exhaust gas of an internal combustion engine of low capacity for desalination using a submerged horizontal tube straight pass evaporator and a condensing unit, without the aid of any external energy used for pumping system. In this work a horizontal tube straight pass evaporator and water cooled condenser for condensing the evaporated steam were designed and fabricated. The experiments were conducted in a 5 hp diesel engine to analyze the performance of the submerged horizontal tube straight pass evaporator (SHTE) under various load conditions. It is evident that 3.0 l/h of saline water can be desalinated from the engine exhaust gas, without affecting the performance of the engine. More over nearly 24 l of water is heated, up to 60 °C in the condenser unit. By utilizing the heat energy in condenser water in addition to waste exhaust gas heat energy the overall efficiency of the system is enhanced and thermal pollution is also reduced considerably.

1. Introduction

The modern world relies very much on diesel engines in so many ways like power generation, transportation, and water pumping. Especially for transportation and power generation it plays a vital role. In the developing countries the main sources of power generation are based on diesel engines and coal based power plants. Even though the cost of producing electricity using diesel engine is higher than any other sources, for hospitals, hotels and in small scale industries where the power requirement is 500 KVA to 1120 KVA, the diesel engines are mainly used due to easy starting and reliability. It is used as an emergency source of power. While considering the transportation, from light motor vehicles to heavy trucks, diesel engine plays a main role. The unutilized heat energy rejected to the atmosphere by the engines are high, the heat from the engine rejected to the atmosphere by 3 ways one from the exhaust gases from the engine, the second heat liberated in cooling towers / radiators, and the third radiation. Thus the thermal pollution caused by the IC engines creates climatic changes and reduces the fresh water availability. Water resources are necessary for the economic growth of a country. Without water sources there is no industrial development. The need for fresh water increased in this year because of rapid industrial growth and population explosion. Due to manmade pollution the rivers as well as ground water get polluted, which results in the reduction of available fresh water. Mobilization of population towards cities for job is another issue. Thus the need makes the people to think of methods to produce fresh water. This study makes an attempt to solve the above issues, desalination using exhaust waste heat energy. Even though all the exhaust waste energy cannot be recovered, some quantity can be utilized for desalination and at the same time it will reduce the thermal pollution also. The availability of waste heat for utilization depends upon the engine size and recovery system.

Pandiyarajan and Chinna Pandian [1] in their study made a shell and finned tube heat exchanger integrated with an IC engine setup to

* Corresponding author.
E-mail addresses: kali_vel@rediffmail.com, kkmmech@nec.edu.in (K. Kalidasa Murugavel).

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extract heat from the exhaust gas, and they stored the thermal energy in a storage tank. They conducted their experiments in a twin cylinder, four stroke, water cooled, Kirloskar make diesel engine (bore 87.5 mm, stroke 110 mm, rated power 7.4 kW at 1500 rpm). Hung and Shai [2] in their study deal with the utilization of the waste heat streams, jacket water and exhaust gas from a diesel engine as the heat source for desalination of seawater. They conducted their study on a 10 MWe diesel engine. Hiroshi Tanaka and Park [3] utilized the waste heat from portable electric generator to increase the productivity of desalinated water in solar stills. They numerically analyzed a vertical multiple-effect diffusion still utilizing energy from waste gas from a portable electric generator by means of a heat-pipe to determine the basic behavior of distillation and the productivity of the still in steady-state. Brandon A. Moore et al. [4] in their paper described a new water distillation process that uses sub-atmospheric pressure, and hence low temperature to boil water. The process is made to run with sources of low quality heat energy sources. Corrado Sommariva [5] in his paper described the innovative process configurations where MSF/MED plant performance ratio and production are optimized taking advantages of waste heat steam made available from different process steams in a power plant. Hafizur Rahman et al. [6] used submerged vertical tube evaporator (SVTE) in their study to utilize waste heat from an engine. The heat energy was used to produce both power and water. Soteris [7] in his work designed a low-cost evaporator. The new type of evaporator suggested by him was of the spray-type, i.e., spaying the seawater into fine droplets to evaporate the water. The evaporator was designed based on the theory of cooling towers. The performance of a finned-tube evaporator used to recover exhaust waste heat from a diesel engine was presented by Zhang et al. [8].

Desai and Bannur [9] conducted experiments in a twin cylinder diesel engine, to recover heat energy from engine exhaust using a shell and tube heat exchanger. Morcos [10] has studied the performance of shell and dimpled tube heat exchangers for waste heat recovery. The exchanger heat duty, overall heat transfer coefficient, effectiveness and tube side friction factor were investigated in their study. Lee et al. [11] have done experimental study on the effects of secondary combustion efficiencies and emission reduction in the engine exhaust heat recovery system. Medrano et al. [12] experimentally studied the performance of PCM RT35 on five different heat exchangers during charging and discharging. Talbi and Agnew [13] have examined the interfacing of turbocharged diesel engine with an absorption refrigeration unit and estimated the performance enhancement due to the energy recovery from the engine exhaust gas. Anderson and Robert Nation [14] have done work in waste heat recovery system for an internal combustion engine exhaust gas and coolant using two different liquids operating at different pressures and temperatures in two separate circuit paths. In the study of Zare et al. [15], the waste heat from a gas turbine-modular helium reactor (GT-MHR) is utilized to produce power through two Organic Rankin Cycles (ORCs) and pure water by means of distillation processes. An absorption heat transformer (AHT) is employed to upgrade the lower temperature waste heat in order to run the desalination system. They concluded that for each 50 °C increase in the gas turbine inlet temperature, the thermal efficiency is increased by around 2.5–4% and the pure water production rate is decreased by around 6.5%. In the study of Kiyan Parham et al. [16], alternative configurations of absorption heat transformer (AHT) systems using $LiBr/H_2O$ as the working fluid and integrated with a water purification system are analyzed and optimized thermodynamically. The waste heat from a textile factory is utilized to run the AHT systems and the generated high temperature heat is employed for the purpose of desalination. In the study of Cardona et al. [17], a small size (2000 m^3/day) thermal desalination system (MEE) is coupled with a single-stage seawater reverse osmosis (SWRO) system and a natural gas (NG) reciprocate engine, where heat is recovered both from exhaust gases and from the cooling jacket water to reduce the unit cost of desalted water. Francisco [18] carried out thermo-economic analysis and simulation of a combined power and desalination plant, developed the complete thermo-economic analysis for an existing steam power plant and MSF desalination unit, including cost analysis, diagnosis and local optimization of the plant. The results demonstrate the effect of different conditions or inefficiencies in terms of water and energy costs and additional fuel consumption during an inefficiency.

2. Description of the system

The various types of energy available in the flue gas are kinetic energy, thermal energy and pressure energy, while considering the direct energy conversion which requires more pressure and kinetic energies, the exhaust gas is considered as a low grade energy as the gas is at low pressure and high temperature. But the availability of thermal energy in the flue gas can be converted into useful work by means for heating or evaporating. This study is an indirect recovery method that utilizes the thermal energy of the exhaust flue gas for desalination. Designing of heat recovery system for utilizing the thermal energy of an engine exhaust is a complicated one as the obstruction in the exhaust gas affects the performance of an engine.

In this study we decided to use the thermal energy of the exhaust flue gas for desalination using a submerged horizontal tube straight pass evaporator (SHTE), to avoid the energy loss by using two or three heat exchangers. As shown in Fig. 1 the experimental setup consists of an evaporator, water cooled condenser, storage tanks for storing the hot saline water, preheated saline water in the condenser and potable water. The exhaust gas from the engine is allowed to pass through the evaporator, and the saline water which is in the evaporator gets the heat from the engine exhaust and evaporated. The evaporated steam is passed through the water cooled condenser and condensed. The condensed water is of potable quality, which is collected by a fresh water tank. The hot water from the condenser is collected and stored in a hot water storage tank.

3. Experimental methodology

3.1. Experimental equipment description

The available energy in the exhaust gas varies with the capacity, speed and the load of the engine. With the engines running at a constant speed, the exhaust energy varies only with the load on the engine. Maximum heat extraction rate from the exhaust flue gas is calculated through the lab experiments conducted at various engine load conditions. The flue gas quantity and the flue gas temperature increase with the load. The results showed that the available heat energy in flue gas increased by 25%–35% for every 25% load raise. The maximum energy of 3 kJ/s is obtained when the engine is running at a maximum load considering that the flue gas is cooled up to the atmospheric temperature. However, it is not possible because of a) as the gas pass through the water which is at boiling temperature in atmospheric condition, b) to avoid sulphanization due to the presence of sulfur in the fuel. Hence in design calculation the exhaust gas temperature at the outlet of the evaporator is considered at 120 °C. In this work the evaporation is taking place in the atmospheric condition.

3.1.1. The evaporator

The evaporator needs an additional space for the evaporation of water, at the same time that the heat energy available is low so that the heat extraction arrangement is also made in the same evaporator itself, which limits the maximum extraction level. The designed tubes are fixed at the bottom of a shell and tube heat exchanger. The saturated vapor is collected above the water level. In this study energy in exhaust flue gas is estimated by measuring the outlet temperature from the evaporator (120 °C). The heat extraction rates from the exhaust gas through the waste heat recovery evaporator are calculated at different

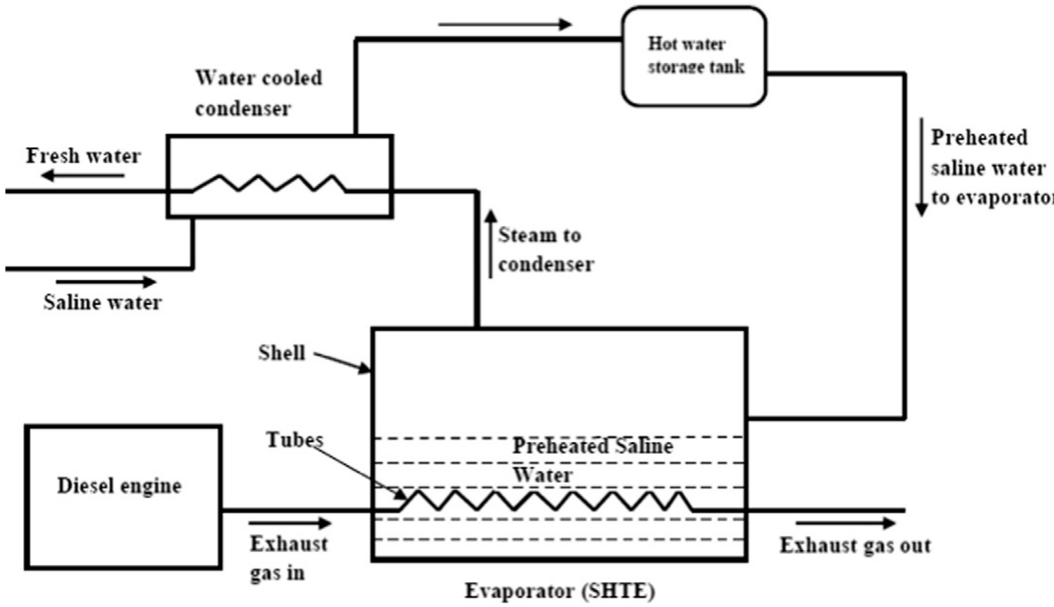

Fig. 1. The schematic diagram of the experimental setup.

loads by using the equation

$$Q_{ext-e} = m_g \times C_g \times \left(T_{gi} - T_{go}\right) \quad (1)$$

where, m_g — mass flow rate of flue gas in kg/s and T_{gi} and T_{go} are the temperatures of exhaust gas at the inlet and outlet of submerged horizontal tube evaporator. The maximum thermal power recoverable is 1.36 kJ/s using SHTE (Eq. (1)). For distillation of water both sensible and latent heats are required. For evaporating the water from atmospheric temperature the thermal power required is

$$Q_{req} = m_{sw}C_{sw}(\Delta T)_{sw} + m_{sw}L_{sw}. \quad (2)$$

Thermodynamic first law yields the energy balance, and the heat carried out by the water in the evaporator is equal to the heat lost by the flue gas (Eqs. (1), (2)).

$$m_g \times C_g \times \left(T_{gi} - T_{go}\right) = m_{sw}C_{sw}(\Delta T)_{sw} + m_{sw}L_{sw} = m_s L_s. \quad (3)$$

Based on the heat energy estimation, the heat transfer area and number of tubes were calculated.

$$Q_{ext-e} = U_e A_e (T_f - T_b) \quad (4)$$

To find the overall heat transfer coefficient (U_e)

$$1/U_e = (1/h_{ie}) + Rf_{ie} + (r_{ie}/k)\ln(r_{oe}/r_{ie}) + (r_{ie}/r_{oe})Rf_{oe} + (r_{ie}/r_{oe})(1/h_{oe}). \quad (5)$$

Table 1
Design details of evaporator.

Sl. No.	Name of the components	Dimension in m	Material used
1	Dia of the exhaust tubes (number of tubes — 7)	0.012	Copper
2	Length of the exhaust tubes	0.5	Copper
3	Dia of the shell	0.15	Mild steel
4	Length of the shell	0.8	Mild steel
5	Dia of the feed water tube	0.006	Copper

The area of the evaporator is calculated by

$$A_e = Q_{ext\text{-}e}/(U_e \times (T_f - T_b)) = \pi d_{cte} l_{cte} N_{te}. \quad (6)$$

Number of the tubes is calculated by

$$N_{te} = A_e/\pi d_{cte} l_{cte}. \quad (7)$$

Based on the number of tubes, the shell diameter was considering the pitch ratio and tube pitch for the evaporator. The design details of evaporator are shown in Table 1 (Fig. 2).

3.1.2. Water cooled condenser

The water cooled condenser was designed based on the evaporation rate as follows.

Condenser heat load Q_c is

$$Q_c = m\left(h_{fg} - h_f\right). \quad (8)$$

For condenser, by neglecting losses, the energy balance is, the heat liberated by the vapor is equal to the heat absorbed by the saline

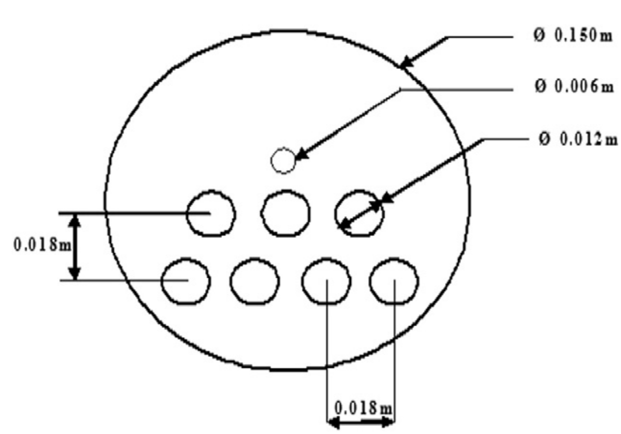

Fig. 2. Cross sectional view of the evaporator.

Table 2
Design details of water cooled condenser.

Sl. No.	Name of the components	Dimension	Material used
01	Dia of the tube	0.012 m	Copper
2	Length of the tube	0.6 m	Copper
3	Dia of the shell	0.1 m	Mild steel
4	Length of the shell	0.4 m	Mild steel
5	Number of passes	2	–

water, and given by:

$$m_s L_s = m_d C_{pd} (\Delta T)_d + m_{sw} C_{sw} (T_{sw2} - T_{sw1}). \tag{9}$$

Considering for one shell pass and two tube condensers,

$$Q_c = F \times U_c \times A_c \times \Delta T_{lm}. \tag{10}$$

To find the overall heat transfer coefficient U_c

$$1/U_c = (1/hi_c) + Rf_{ic} + (r_{ic}/k)\ln(r_{0c}/r_{ic}) + (r_{ic}/r_{0c})Rf_{oc} + (r_{ic}/r_{0c})(1/h_{0c}). \tag{11}$$

The area of the condenser is calculated by

$$A_c = Q_c/(F \times U_c \times \Delta t_{lm}). \tag{12}$$

The length of the tube is calculated by

$$A_c = \pi d_{ctc} l_{ctc} N_{tc} \tag{13}$$

$$l_{ctc} = A_c/[\pi d_{ctc} N_{tc}]. \tag{14}$$

Based on the length of tube, the number passes are calculated. From the number of passes the shell diameter of the condenser was designed. The design details of the condenser are shown in Table 2 (Fig. 3).

4. Experimental procedure

4.1. Experimental setup

The experimental setup consists of a single cylinder, four stroke, water cooled, Kirloskar make diesel engine (bore 80 mm, stroke 110 mm, rated power 5 hp at 1500 rpm) coupled to an electrical dynamometer, and integrated with the heat recovery unit. The heat recovery evaporator is a shell and tube type evaporator and is connected in the exhaust gas path of IC engine. The exhaust flue gas from the engine is passed in the tube side which is surrounded by the saline water. The exhaust gas temperature at the inlet and outlet of the evaporator is measured using a thermocouple. The feed water from the saline water tank is fed to the evaporator through control valves which controls the flow of water to the evaporator. The evaporated steam from the evaporator is passed through the water cooled condenser, and the potable water is collected by fresh water tank and hot water is collected from the condenser; it is stored by preheated water tank. The photographic view of the entire experimental set up of the system is shown in Fig. 4.

Fig. 4. Experimental setup.

While the experimental readings are conducted, the saline water and preheated saline water from the storage tank passed to the evaporator through the control valve which controls the flow of feed water in the evaporator. The evaporated steam is exhausted through the pipe line which is fitted above the evaporator. Suitable drain arrangements and measuring arrangements were provided in the evaporator. To calculate the performance of the evaporator for its efficiency of producing pure water from the input saline water, parameters like inlet and outlet temperatures of water, velocity and mass flow rate of distilled output water are to be measured. Thermowells are provided in the required areas of the evaporator and they were insulated with mineral wool and aluminium cladding was provided to avoid heat loss.

5. Results

Two types of experiments were conducted in this work: feeding the water to the evaporator without preheating and preheating the feed water to 60 °C before feeding into the evaporator. In the first experiment the water used in water cooled condenser is stored in a separate

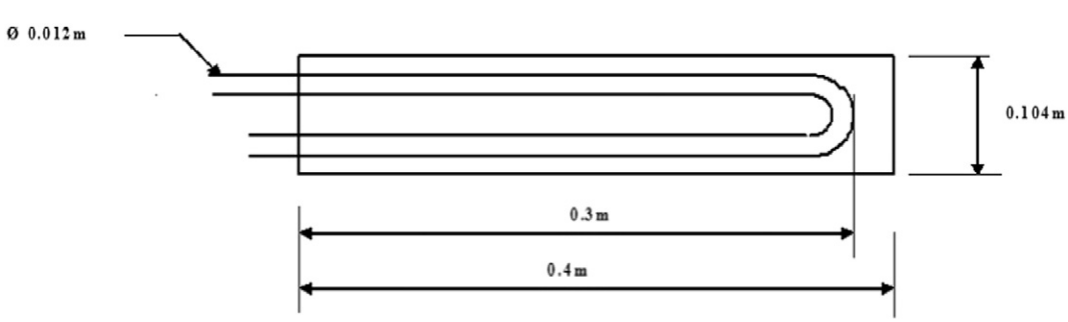

Fig. 3. Dimensions of condenser.

Table 3
Experimental readings with water cooled condenser (without preheating).

Sl. No.	Load (%)	Exhaust gas temp at the inlet of evaporator (°C)	Exhaust gas temp at the outlet of evaporator (°C)	Evaporation rate (l/h)	Fresh water collection rate (l/h)
1	25	230	105	0.8	0.8
2	50	280	110	1.0	1.0
3	75	330	115	1.2	1.2
4	100	410	120	1.8	1.8

Table 4
Experimental readings with water cooled condenser (with preheating).

Sl. No.	Load (%)	Exhaust gas temp at the inlet of evaporator (°C)	Exhaust gas temp at the outlet of evaporator (°C)	Evaporation rate (l/h)	Fresh water collection rate l/h
1	25	230	105	0.8	0.8
2	50	280	110	1.5	1.5
3	75	330	115	2.25	2.25
4	100	410	120	3.0	3.0

insulated tank and for the evaporator the water is fed from the saline water tank at 30 °C. The experiments were conducted at 25%, 50%, 75% and 100% loads for a time period of 100 min. The output quantity of desalinated water is measured at various load conditions such as 25, 50, 75 and 100%, for the time period of 100 min at each load. The flow rate of feed water to the evaporator is kept at 2 l/h. Measurements such as rpm of the engine, ammeter and voltmeter readings of alternator, exhaust gas temperature at the inlet and outlet of engine, cooling water flow rate of condenser, quantity of fuel, and quantity of potable water are done using proper instruments. In this work attempts have been made to recover the maximum available heat in the exhaust flue gas through submerged horizontal tube evaporator and to utilize it for producing fresh water by the distillation desalination process. As the engine load increases the exhaust temperature also increases according to its higher heat release from the engine and also fresh water collection rate is increased, which is tabulated in Table 3.

In the second experiment the water used in water cooled condenser is stored in a separate insulated preheated water tank and fed to the evaporator through the control valves. The readings were taken at 25, 50, 75 & 100% loading keeping the feed water flow rate at 3.5 l/h and the feed water temperature at 60 °C (with preheating). Exhaust gas temperatures & evaporation rate with respect to engine loads which is tabulated as follows in Table 4.

The exhaust flue gas temperatures at inlet & outlet of the evaporator are measured with different times and plotted at 25%, 50%, 75%, and 100% load conditions. Fig. 5 showed the temperature variations of the exhaust gas at the inlet and outlet of the HRHE at various load conditions.

In Fig. 5a–d, it is observed that the evaporation started after 15–20 min i.e. when the outlet temperature of flue gas stabilized and it continues up to the end of the trial. The trial at each load was conducted for a duration of 100 min.

It is also observed that when the engine load increases the difference between inlet and outlet temperatures of waste flue gas increases and that heat is used for producing more amount of fresh water collection. The fresh water collection rate without preheating and with preheating the feed water to 60 °C before feeding into the evaporator is shown in Fig. 6. The experimental results showed that the fresh water collection is more with feed water preheating than feed water without preheating.

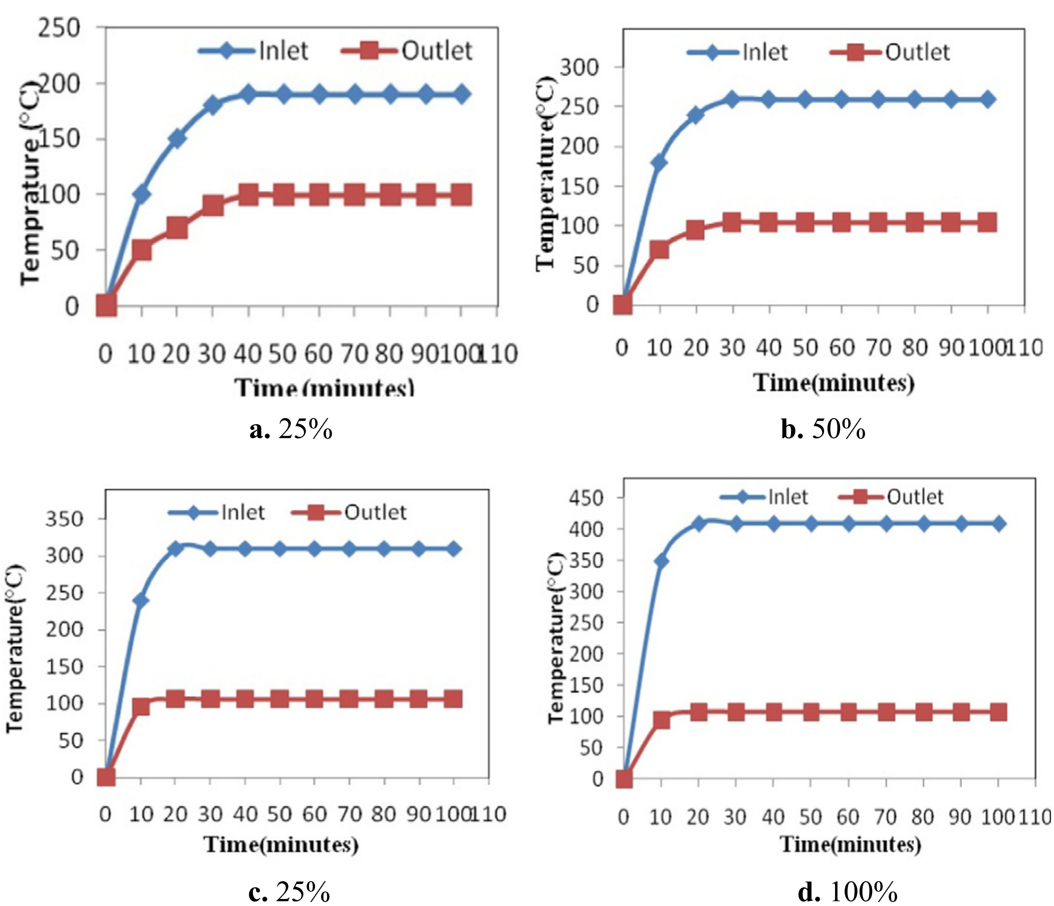

Fig. 5. (a) 25%, (b) 50%, (c) 75% and (d) 100%.

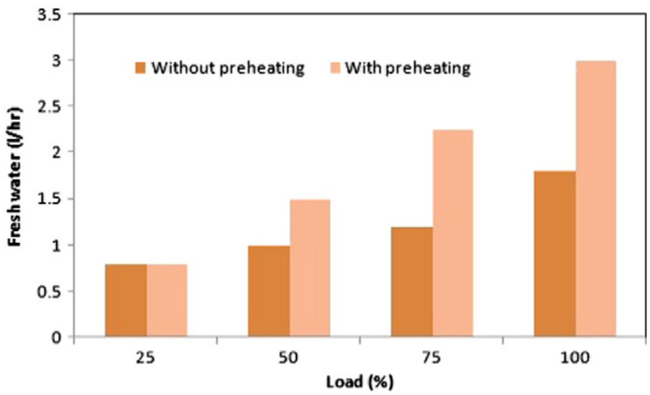

Fig. 6. Fresh water collection rate without and with preheating of feed water.

Fig. 6 also showed that fresh water collection rate is increased because of increase in engine load. In the low load operation that is at 25% load there is no variation in evaporation rate with and without preheating, this is because of the exhaust temperature of the flue gas which limits the heat transfer driving force.

While considering the engine running for 8 h/day and 300 days in a year, the fresh water production rate is 7200 l/year. The production cost of fresh water through RO system is Rs1/l. Hence the payback period is 2 years of the project cost is Rs13,000. Even if the engine runs for 150 days in a year, the production is 3600 l/year and the payback period will be 4 years. In the case of 50% load and engine running for 8 h/day and 300 days in a year also the production rate is 3600 l.

6. Conclusion

The aim of this work is to utilize the heat energy wasted in the exhaust gas of IC engine for desalination. A horizontal tube straight pass evaporator is used to absorb the heat energy from IC engine. The steam from the evaporator is passed through the water cooled condenser and the fresh water is collected. For cooling the steam from the evaporator, the saline water itself is used and it is stored and fed to the evaporator.

The experimental setup was designed, fabricated (evaporator, water cooled condenser without and with preheating) and connected to the 5 hp Kirloskar make single cylinder diesel engine. The evaporation rate of water with respect to various engine load conditions is analyzed. The results are summarized below.

1. The desalinated water output is considerably increased while using water cooled condenser with preheating than water cooled condenser without preheating.
2. In the condenser the saline waters itself were used as a cooling media to cool the steam from the evaporator. It gets heated up to 60 °C and stored in the separate insulated water tank. We can effectively utilize the same preheated water temperature for other useful purposes.
3. In future desalination also can be done by using the water with some other low temperature evaporation systems like flash evaporation thereby the desalination rate can be increased further.

Nomenclature

Abbreviations

HRHE	heat recovery heat exchanger
SHTE	submerged horizontal tube evaporator
WCC	water cooled condenser

Symbols

$(\Delta T)_{sw}$	change in temperature of saline water, K
$(\Delta T)_{d}$	change in temperature of distillate water, K
A_c	heat transfer area of the condenser, m^2
A_e	heat transfer area of the evaporator, m^2
C_g	specific heat capacity of flue gas, kJ/kg K
C_{pd}	specific heat capacity of distillate water, kJ/kg K
C_{sw}	specific heat capacity of saline water, kJ/kg K
d_{ctc}	diameter of the copper tube in condenser, m
d_{cte}	diameter of the copper tube in evaporator, m
F	correction factor
$h_{ie,}$ h_{oe}	inside and outside heat transfer coefficient of evaporator, W/m^2K
k	thermal conductivity of copper, w/mk
l_{ctc}	length of the copper tube in condenser, m
l_{cte}	length of the copper tube in evaporator, m
L_s	latent heat of steam, kJ/kg
L_{sw}	latent heat of evaporation of saline water, kJ/kg
m_d	mass flow rate of distillate water, kg/s
m_g	mass flow rate of exhaust flue gas, kg/s
m_s	mass flow rate of steam, kg/s
m_{sw}	mass flow rate of saline water, kg/s
N_{tc}	number of tubes in the condenser
Nt_e	number of tubes in the evaporator
Q_e	available heat energy in the evaporator, kJ/s
Q_{ext-e}	heat extraction rate from evaporator, kJ/s
Q_{req}	heat energy required to evaporate the water, kJ/s
Rf_{ic}, Rf_{oc}	inside and outside fouling resistance in condenser
Rf_{ie}, Rf_{oe}	inside and outside fouling resistance in evaporator
$r_{ie,}$ r_{oe}	inner and outer radii of the evaporator tubes, m
T_b	boiling point of water, K
T_f	temperature of the flue gas, K
T_{gi}	temperature of exhaust gas at the inlet of the evaporator, K
T_{go}	temperature of exhaust gas at the outlet of the evaporator, K
T_{sw1}, T_{sw2}	inlet and outlet temperatures of saline water in condenser, K
U_c	overall heat transfer coefficient of condenser, W/m^2K
U_e	overall heat transfer coefficient of evaporator, W/m^2K
ΔT_{lm}	logarithmic mean temperature of condenser, K

Subscripts

ctc	copper tubes in the condenser
cte	copper tubes in the evaporator
d	distilled water
ext	extracted
s	steam

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